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SEDG: Scalable and Efficient Data Gathering Routing Protocol for Underwater WSNs

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Abstract

In recent years, the use of Autonomous Underwater Vehicle (AUV) along a constrained path can improve the data delivery ratio and maximize the energy efficiency in Underwater Wireless Sensor Networks (UWSNs). However, constant speed of AUV leads to limited communication to collect data packet from nodes deployed randomly in large scalable network. Moreover, the excessive number of associated nodes with Gateway Node (GN) causes to quick depletion of its energy, thus lead to hot spot problem. This poses prominent challenges in jointly improving the throughput with minimum energy consumption. To address these issues, we presented a novel scalable data gathering scheme called Scalable and Efficient Data Gathering SEDG routing protocol, that increases the packet delivery ratio as well as conserves limited energy by optimal assignment of member nodes with GN. Moreover, the variable sojourn interval of AUV decreases the packet drop ratio and hence, maximize the throughput of network.

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Keywords: UWSNs, AUV, GN, Lifetime, Network throughput, End-to-end delay

1. Introduction

UWSN attracts the researchers due to its various applications in seas and oceans such as seismic monitoring, management of seabed and oil mines detection. UWSN consists of nodes that might be randomly or uniformly deployed in the ocean. These nodes sense different parameters like velocity of currents to detect tsunami and send data to sink which relays it to surface station. The nodes are deployed near the surface or in deep water depending upon the application. Other applications of UWSN include coastline surveillance, tactical surveillance to the study of marine life and oceanographic data collection.

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Variable and unpredictable conditions of underwater environment lead to lots of challenges in efficient data gathering and maximization of network lifetime i UWSN. Underwater wireless communication has lots of limitation and constraints like the speed of acoustic signal is 1500 m/s that is approximately five times less than electromagnetic signal. Furthermore, the bandwidth limitation ($< 100KHz$),leads to low data rate. Moreover, the acoustic signal is subject to severe attenuation and Inter Symbol Interference (ISI) due to drastic conditions of ocean.

The above mentioned challenges and limitations degrade the performance of multi-hop transmission which leads to low packet delivery ratio and high packet error rate in scalable network. Furthermore, underwater sensor nodes require high energy to transmit data packets in large scalable networks having hundreds of nodes randomly deployed over seabed. To tackle this issue, different AUV aided routing protocols has been presented for less dense networks. These protocols have lots of advantages regarding energy efficiency and data delivery ratio. Furthermore, lots of AUV based routing protocols suffer low data delivery ratio and short network lifetime. The constant speed of AUV decreases the sojourn time which leads to low packet delivery ratio. Moreover, the association of member nodes with GN in large scalable network leads to high energy consumption as well as high data loss due to its limited storage capacity.

2. Related Work

In[1], authors presented an underwater analysis to observe the communication challenges that effect the network performance. Authors explored different characteristics of acoustic channel and analyzed their effects on the link layer and network layer. The Unmanned Underwater Robotic System (UURS) usually depends on the reliable acoustic communication channel. However, the small bandwidth and strong signal attenuation effect its performance. The terrestrial routing protocols use radio waves and optical technology for communication, however these techniques are not successful in underwater due to limited range. Due to this reason, acoustic communication is more suitable for underwater environment. However, acoustic communication has lots of drawbacks like limited bandwidth, strong attenuation at high frequency and multi-path fading.

In[2], authors focused on resource exploration and searching tasks autonomously. For this purpose, an underwater localization and mapping strategy is presented. It consists of two algorithms Localization Particle Filter (CLPF) scheme and Occupancy Grid Mapping Algorithm (OGMA). Both algorithms have their own respective tasks. OGMA is used for three dimensional mapping and CLPF is used for three dimensional localization. The detailed formulation of CLPF incldes: probabilistic framework, initialization, prediction, updating and re-sampling. The results which are obtained from CLPF, finally utilized for 3D mapping. In this way an efficient and reliable localization and mapping technique is presented which is far better than previous schemes.

A link-state based feedback routing protocol was presented in[3] for UWSN . Most of the recent protocols do not focus on the beam width of sensor nodes in UWSN. The dimension of beam width is not considered. This characteristic increases the energy consumption and degrades the network performance. To tackle this problems a link detection scheme is presented with feedback mechanism. The energy consumption caused by continuous updating of routing table is overcome by introducing a credit-based routing table updating technique.

In[4], authors presented a protocol named as Mobicast routing protocol for UWSNs. It is most familiar routing protocol for underwater which emphasizes to maximize the throughput and reduces the energy hole problem. The network field is divide into three dimensional zones named as 3-D zones. The path of AUV is predefined and it aggregates the data from a series of 3-D zones. The operation of protocol consists of two phases, the first phase consists of collecting data within a 3-D zone, and the second phase consists of awaking up those sensor nodes in the next 3-D zone to be queried while trying to avoid energy holes. The sensor nodes in 3-D zones are eligible to enter the active mode for the sake of delivering sensed data to passing AUV. Hence, this protocol decreases the energy consumption to overcome unpredictable 3-D hole problem.

A multi-channel contention-free Medium Access Control (MAC) protocol for bursty traffic in UWSNs is present in[5]. The main critical challenges of sensor nodes in underwater have their limited battery and secondly an increased an energy consumption due to multiple transmissions and receptions. The main part of energy consumption is due to collision of data packets in case of bursty traffic. In order to address this problem a new a contention free multi-channel MAC protocol has presented. It is more suitable for uneven and drastic conditions when traffic load increases.

M. Al-Bzoor in[6] presented an adaptive dynamic sink redeployment strategy that enforces redeployment. When the mobility of the network is not severe, nodes tend to use a fixed power level to communicate with neighboring nodes or surface sink. However, if more nodes are switching to use higher power levels for communication and the energy consumption is increased a sink redeployment procedure is started. Surface sink then triggers localization and finds the optimal new location of surface sink to minimize total energy consumption.

A Round-Based Clustering Scheme for Data Redundancy Resolve (RBCSDRR) presented for UWSNs is presented in [7]. Authors presented a cluster based technique to deal with data redundancy. The cluster head selection is based on the residual energy as well as distance from the sink. Data redundancy is reduced by applying data aggregation in the cluster. The intra-cluster and inter-cluster communication setup newly every time when cluster head changes.

Authors in [8], presented an idea to trace out and tackle the particular target in underwater. Research work emphases on nonlinear and maneuvering problems for underwater target tracking based on UWSNs. A three dimensional target tracking algorithm is proposed to track the target. Moreover, in order to enhance the accuracy, multiple model method is combined with the particle filter to handle with uncertainties in target maneuvers.

A Relative Distance Based Forwarding Protocol(RDBF) proposed by authors in [9]. This protocol mainly emphasizes on energy efficiency and low delay in UWSNs. The conditions in underwater are severe, so multi-path fading, long propagation delay and low bandwidth effects the packet delivery ratio. The route from source to destination plays a critical role as for as the above mentioned challenges are concerned. The best forwarder is selected on the basis of fitness factor. A fitness factor relates to every node for the selection of best forwarder. The criteria to participate in the forwarding process depends on the fitness factor. If fitness factor of any node is less than some predefined threshold value, then that node is eligible for data forwarding. Furthermore, transmission time is introduced in order to avoid the duplication of packets. Moreover, for balanced energy consumption, residual energy of nodes is taken into consideration.

In [10], authors describe that AUVs are used to collect sensed data from GNs. In An AUV-Aided Underwater Routing Protocol for Underwater Acoustic Sensor Networks (AURP), the AUV and predefined GNs are deployed in UWSNs. The AUV moves in elliptical path and gather the data from GN. Once the GN die out, the next node having minimum distance with AUV is selected as GN thereby, decreases the stability period of network. Moreover, there is no energy balanced mechanism in AURP. AUVs collect data from GNs and then forward it to static sinks deployed at the surface of water.

In [11], A. Ahmad et. al proposed an energy efficient routing protocol named AEERP for UWSNs. Each sensor node senses data and transmits it to its GN in a specified time. The sensor nodes use the Shortest path Tree (SPT) algorithm to forward data to GNs. Furthermore, a technique of changing GN is also introduced based on their residual energy in order to increase the network lifetime.

3. Delay computation and Energy Consumption model

In this section, we discuss the energy consumption model [12] for acoustic communication. Passive sonar equation is used to calculate Signal-to-Noise Ratio (SNR).

$$SNR = SL - TL - NL + DI \geq DT \tag{1}$$

In eq. 1, *SL* is source level, *TL* is transmission loss, *NL* is noise loss and *DI* is directive index and *DT* is the detection threshold of the sonar. The transmission loss between the communicating nodes can be calculated by using Thorp model [13] as follows:

$$TL = 10log(d) + \alpha d \times 10^{-3}. \tag{2}$$

Where d is the distance between the sender and receiver, α is the absorption coefficient. NL is the noise losses composed of four noise components which are computed by using the eq. 3. It depends upon the frequency (f) of signal:

$$10log(N_t(f)) = 17 - 30log(f), \tag{3}$$

$$10log(N_s(f)) = 40 + 20(s - 0.5) + 26log(f) - 60log(f + 0.03), \tag{4}$$

where w is a wind constant s is a shipping constant.

$$10log(N_w(f)) = 50 + 7.5w^{1/2} + 20log(f) - 40log(f + 0.4), \tag{5}$$

$$10log(N_{th}(f)) = -15 + 20log(f). \tag{6}$$

Where noise produced due to turbulence, shipping, wind and thermal activities are denoted by N_t , N_s , N_w and N_{th} respectively. SL can also be computed by using passive sonar equation.

$$SL = SNR + TL + NL - DI. \tag{7}$$

Transmitted signal Intensity (I_T) can be calculated by using eq. 8.

$$I_T = 10^{SL/10} \times 0.67 \times 10^{-18}. \tag{8}$$

Therefore, the source Transmitted Power ($P_T(d)$) can be calculated by using

$$P_T(d) = 2\pi \times 1m \times H \times I_T. \tag{9}$$

In eq. 9, H shows the depth of the network. It can also be written as:

$$P_T(d) = 2\pi H \times 1m \times H \times 10^{SL/10} \times 0.67 \times 10^{-18}. \tag{10}$$

Energy consumption in sending k bits over a distance d is given as:

$$E_{TX}(k, d) = P_T(d) \times T_{TX}. \tag{11}$$

Transmission time T_{TX} is the time taken by k bits to send over distance d. It is measured in seconds. Delay can be computed by using end-to-end delay model[14]. The propagation delay T_P is the main component of this model.

$$T_P = s/v \tag{12}$$

In eq. 12, s is the distance between the sender and receiver and v is the speed of acoustic signal which can be calculated as follows:

$$\begin{gathered} v = 1449.05 + 45.7t - 5.21t^2 + 0.23t^3 + \\ (1.333 - 0.126t + 0.009t^2)(S - 35) + 16.3z + 0.18z^2 \end{gathered} \tag{13}$$

$$t = T/10 \tag{14}$$

4. Motivation

In UWSNs, the major challenges include low data delivery ratio, multi-path fading, high attenuation and multiple transmissions and receptions which lead to high energy consumption in data transmission. Different routing protocols are presented to tackle the above mentioned challenges. Moreover, multi-hop communication in underwater causes high energy consumption. Therefore, different AUV aided routing protocols are presented in literature to overcome the above mentioned problems. However, these protocols have not considered the following parameters: 1) Dynamic sojourn interval of AUV, 2) Optimal assignment of member nodes with GN, 3) Scalability of network, which leads to low data delivery ratio and high energy consumption. We therefore, propose a novel scalable and energy efficient data gathering scheme for UWSN named as SEDG.

In our research work, we present a criterion for scalable network and how energy consumption is minimized with high data delivery ratio. In our protocol the AUV dynamically assigns the sojourn time to GN on the basis of number of packets received and the number of associated member nodes with it.

5. Scalable and Efficient Data Gathering Routing Protocol for Underwater WSNs: SEDG Protocol

In SEDG protocol we assume that nodes are deployed randomly at the bottom of ocean. AUV traverses the network on predefined elliptical path and gathers the data from GNs as shown in fig. 1(a). Moreover, computational capabilities and energy of AUV is unlimited. Furthermore, the localization of AUV and sensor nodes is known by any localization method.

The selection of GNs is on the basis of Received Signal Strength Indicator (RSSI) value. The member nodes are attached with GN through Shortest Path Tree (SPT), and number of member nodes are restricted to make the protocol energy efficient. Communication time of AUV with GN is varied according to number of associated member nodes. The protocol is efficient in scalable network.

SEDGs operation from network establishment to data transmission is divided into two phases; setup and steady state. During setup phase, preliminary activities for data transmission like elliptical movement of AUV, determination of GNs, chain formation using SPT, restricting number of member nodes and allocation of variable sojourn interval are carried out. After setup phase data transmission(s)/reception(s) is(are) accomplished during steady state phase.

5.1. Setup Phase

In setup phase, following activities are carried out in sequence:

- Random deployment of nodes at the bottom of ocean.
- AUV moves on predefined elliptical trajectory and has global knowledge of network.
- AUV transmits hello packetafter a specific interval of time.
- Selection of GNs on the basis of RSSI value of hello packet (nodes with highest RSSI value of hello packetare selected as GNs).
- Association of member nodes with GN through SPT.
- Restricting the number of member nodes with GN in order to reduce extra burden on it.
- Allocation of variable sojourn time to AUV on the basis of number of member nodes associated with GN.

5.1.1. Deployment of Nodes

In underwater environment, nodes are deployed to monitor any particular area depending upon the application. The number of nodes and the deployment strategy vary from application to application. In general, there are two fundamental ways of node deployment; deterministic and random. The deterministic strategy is impractical in applications like underwater mine detection and other military applications. The random deployment strategy is sometimes more practical and the only feasible one in such applications because it is less time consuming. We deployed the nodes randomly on the floor of ocean. So x number of nodes are randomly deployed in the field of 500×500 m^2 in such a way that x is varying from 100 to 1000 nodes. We evaluate the performance of our proposed protocol by varying the number of nodes.

5.1.2. AUV Movement Pattern

In our proposed SEDG protocol, we select the elliptical path for movement of AUV. The general equation of ellipse is given below.The elliptical movement of AUV and formation of GNs is shown in 1(a).

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \tag{15}$$

The equation of ellipse that we used for AUV movement in SEDG protocol is given below.

$$\frac{(x-h)^2}{a^2} + \frac{(y-k)^2}{b^2} = 1 \tag{16}$$

Where a and b are the major and minor axis of ellipse such that $a > b$, the centre of ellipse is (h,k).

5.1.3. Restriction on Number of Member Nodes of GN

Before the formation of SPT, the member nodes that are attached with GN through SPT are restricted to some particular threshold. For instance, the optimal number of members associated with GN for reduced energy consumption. In this case, we assign optimal number of member nodes with GN in order to reduce the energy consumption at GN. The purpose of this restriction is to reduce the burden on GN. Hence, energy consumption of GN is minimized which reduces the overall energy consumption of network.

5.1.4. Chain Formation

The member nodes are attached with GN through SPT algorithm. The member nodes form a chain to deliver data to GN which finally transmits it to AUV. Chain formation depends on the RSSI value of hello packet transmitted by AUV. When chain is formed, each member node forwards its data to GN. The AUV conduct *Energy Test* to check the residual energy of each member node. The member nodes whose residual energy is greater than zero participate in the chain formation of SPT.

5.1.5. Sojourn Time of AUV

Once the number of member nodes are restricted, the sojourn time of AUV is defined for each GN. The sojourn time of AUV is defined as the time of its stay at any sojourn location to collect data from the GNs. The path of AUV is elliptical and it varies its sojourn time depending upon the number of member nodes associated with GN, and the number of packets transmitted.

5.2. Steady State Phase

Once the setup phase is completed, data transmission and reception is carried out in steady state phase. Member nodes forward the data through SPT. The GN received the data from member nodes and transmit to passing AUV. As the network evolves, the energy of GN depleted. In order to balance the energy consumption and overcome the energy hole problem, the role of GN is rotated on the basis of residual energy. To balance energy consumption, the residual energy threshold mechanism is introduced. Once the energy of GN reaches to threshold, it simply broadcast the *GN leaving* message. The neighboring node listen this message and share their residual energy with each other. The node whose residual energy is greater among its neighbors is elected as next GN. As the GN changes, member nodes associate themselves to new elected GN through SPT.

This process repeats until all the nodes in the field deplete their energy, and the whole network expires. Hence, in our proposed SEDG protocol we focus on the movement pattern of AUV in scalable network, chain formation of member nodes through SPT, restriction on number of member nodes and variable sojourn time for each GN. Moreover, the SEDG perform well as compared to other protocols in scalable network to test the performance of different parameter like throughput, energy consumption and network lifetime.

6. Performance Evaluation

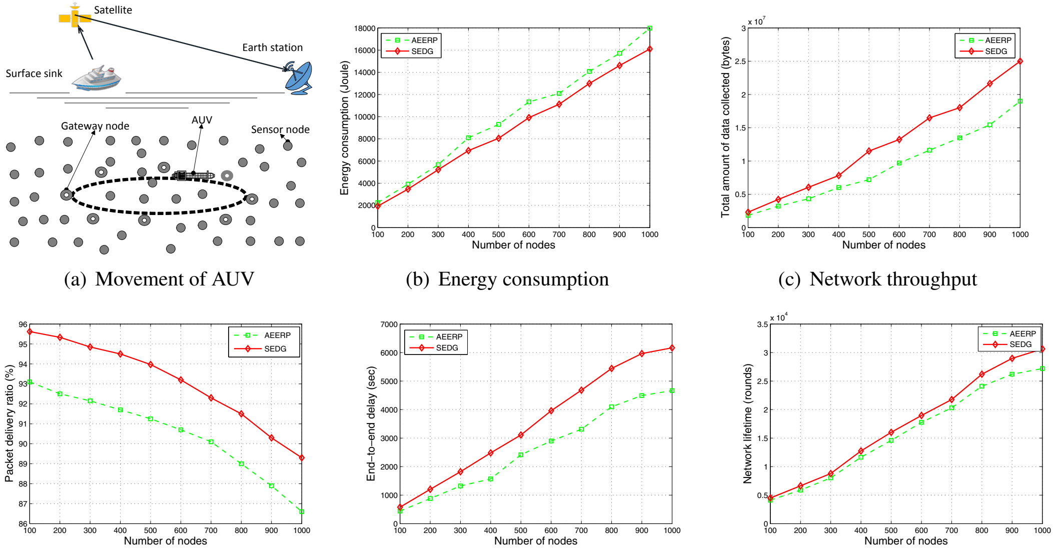
Network size is 500 m×500 m, Number of nodes are 100-1000, Initial energy of normal nodes is 70 J, Data aggregation factor is 0.6, Packet size is 70 bytes, Transmission range of sensor nodes is 250 meters, etc.

6.1. Energy Consumption

The comparison of energy consumption for both the protocols i.e. AEERP and SEDG is shown in fig. 1(b). In case of AEERP, GNs selection criteria is based on RSSI value and they are rotated on the basis of residual energy. In this way the energy is balanced throughput the network. However, if large number of member nodes are attached, the GN depletes quickly. It also creates hot spot problem, so rest of network is completely disconnected. The hot spot and high energy consumption problems are tackled by restricting the number of member nodes attached with GN. In case of scalable network SEDG perform well in terms of energy consumption because when number of nodes increases the unbalanced association of member nodes with GN deplete its energy quickly. However, in SEDG, the optimal association of member nodes with GN balances the energy consumption. Therefore, SEDG consumes less energy than AEERP as shown in fig. 1(b).

6.2. Network Throughput

Fig. 1(c) shows the amount of data collected. The amount of data collection depends upon number of alive sensor nodes in the network field. In AEERP, the AUV moves along the elliptical path and collects the data from GNs. The GNs depletes their energy due to relaying too much data of member modes and die out quickly, so data collection



(a) Movement of AUV (b) Energy consumption (c) Network throughput

(d) Packet delivery ratio (e) End to End Delay (f) Networl Llife-time

Fig. 1. Performance Analysis with respect to Network Lifetime

decreases with the death of sensor nodes. However, in SEDG the association constraint of member nodes with GNs keep the nodes alive for long duration which increases the network throughput. The more nodes alive for long duration and hence the more data is sensed by sensor nodes and collected by MS. Fig. 1(c) shows that SEDG performs better as compared to AEERP in scalable network.

6.3. Packet Delivery Ratio

This is the ratio of packets received by AUV to the total number of packets generated by the network to send information. Fig. 1(d) shows the packet delivery ratio of both the protocols i.e. AEERP and SEDG. Packet delivery ratio normally depends upon the number of nodes in the network and speed of AUV. Firstly if network is sparse and not connected well then delivery ratio reduced, secondly if network is too congested and there are multiple nodes transmit and receive. As large number of transmission and reception increase the chances of collision so data delivery ratio decreases. In AEERP, AUV moves with constant speed and it has no specific sojourn location. The constant speed of AUV enhances the chances of data loss, because GN has very limited communication time with AUV. If GN has more data to deliver, and it has limited time to send data then packet drop ratio increases. The fig. 1(d) depict that as number of nodes increase, the packet delivery ratio decreases in both protocols. However, in SEDG the AUV adjusts its communication time with GN in order to decreases the data loss and increase the packet delivery ratio. Hence, SEDG performs well in scalable network as compared to AEERP.

6.4. End-to-end Delay

The end-to-end delay of AEERP and SEDG is shown in fig. 1(e). The speed of acoustic signal and the transmission distance impacts the end-to-end delay. The speed of acoustic signal is varying from 1450 m/s to 1500 m/s and s is the distance between transmitter and receiver. Hence, end-to-end delay depends upon the distance between source node and destination. The end-to-end delay increases with increment of accumulative distance. In case of scalable network, SEDG has maximum number of alive nodes for longer duration and hence transmission distance increases which leads to increases the end-to-end delay. Moreover, end-to-end delay depends on the speed of AUV and time required to complete one cycle. In AEERP, AUV moves with constant speed on predefined trajectory irrespective of any sojourn location. In this way, the end-to-end delay of AEERP is minimum than previous protocols. However, in SEDG, AUV varies its speed on any particular sojourn location depending upon data packets. The AUV increases its speed where GN has less packets to transmit and decreases its speed where more data is to be collected. So in this way, SEDG has more end-to-end delay as compared to AEERP as shown in fig. 1(e).

6.5. Network Lifetime

Fig. 1(f) shows the network lifetime of both the protocols, AEERP and SEDG. Network lifetime depends on the rate of energy consumption of nodes. As we know that conditions in underwater are very harsh so multiple transmissions and receptions increase the energy consumption of sensor nodes. In AEERP, the nodes forward their data through SPT and GNs are selected on the basis of residual energy. In this way overall energy of network is balanced, however excessive number of member nodes with GN depletes its energy more quickly and hence network lifetime is decreased. In SEDG, the restriction on number of member nodes association decreases the energy consumption. As the number of sensor nodes increases, our protocol performs well, because with increasing number of nodes the number of GNs also increase which balance the energy consumption of whole network. Moreover, the optimal number of member nodes assigned with GN leads to reduced energy consumption.

7. Conclusion and Future Work

In this paper, we presented a scalable and efficient data gathering scheme for UWSNs with controlled mobility of AUV. In SEDG, the association of limited member nodes with GN enhances the network lifetime and also balances the energy consumption. Furthermore, the dynamic sojourn interval of AUV with GN maximizes the packet delivery ratio. Moreover, changing GNs on the basis of residual energy maximize the network lifetime. Simulation results depict that, SEDG performs well as compared to AEERP in scalable network in terms of throughput and energy consumption. In future, we will implement our technique in different scenarios with various trajectories of AUV. We also plan to investigate the optimal trajectory of AUV for efficient data gathering with network lifetime maximization.

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